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A Study on Ejected Flames

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Abstract

To obtain knowledge to prevent upward fire spread caused by ejected hot gas, experimental studies have been done by using reduced-scale models of a high-rise apartment building. It is believed that the balcony configuration influences air flowing in through opening, hot gas ejected out through an opening, and flow outside the fire room. Changing balcony configuration, temperatures inside and outside of the fire room were measured and analysed. The following results were derived. Temperature in the fire room varied with balcony configuration. To evaluate the effects of balcony configuration an 'enclosure ratio' was introduced. Temperature in fire room increased with the enclosure ratio. The probability of upward fire spread was evaluated by the temperatures on the outer wall and the temperature at the exits of balcony. The probability was dependent on balcony configuration. Temperature obtained by CFD simulation was in qualitative agreement with experimental results.

1. Introduction

If a fire develops fully in a room, it may spread to upper floors. According to the Tokyo Fire Department[1], more than thirty cases of fire spread in fire-resistive buildings are reported every year. Fire spread to upper floors is caused mainly by openings in outer wall. The mechanism involved in fire spread caused by the opening is breaking of window glass by hot gas flowing along outer building walls from lower floors and ignition of combustibles in rooms by hot gases entering through the opening. In the Tokyo area, there are 130,000 buildings which have four storeys or more[2]. Apartment buildings constitute more than one-third of them. Upward fire spread caused by openings on the outer wall occurs mainly in apartment buildings. Most of apartment buildings have balconies on their outer walls. Fire departments expect that balconies are used for escape routes in an emergency, fire-fighting activity, and prevention of upper fire spread.

The research on ejected flames and role of balcony on preventing upward fire spread started from 1997 and continued for 5 years.

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The brief history of the research is shown in Table 1. The flow of the research is shown in Figure 1. Full details are shown in the final report of the research[3].

Experimental studies on the role of a balcony for prevention of upward fire spread have been done. Yokoi[4], Iwai et al.[5], Yamaguchi et al.[6], and Wakasa et al.[7] used reduced-scale models. Oleszkiewicz[8, 9] used a real-scale model. In their studies, one or two balconies were set above the opening. As shown in Figure 2, observing real apartment buildings, the balcony configuration has the following features.

Balcony is set on outer wall of each floor.

Depth of balcony varies according to building.

Balustrade is installed at exits of balconies.

Configuration of balustrades varies according to building.

Separation walls are installed between neighbouring dwelling units.

Since model configurations used in previous studies are different from those of real apartment buildings, more information is needed to prevent upward fire spread in apartment buildings. To obtain needed information, it is preferable to use a model building constructed with balcony configurations seen on real apartment building.

Kudoh et al.[10] studied the effects of balcony configuration on ejected flames by using a 1/15-scale model building whose balcony configuration is similar to a real one. The number of thermocouples was not enough to get detailed temperature distribution outside the fire compartment.

The authors have reported results obtained by using a 1/7-scale model apartment building of 3.4 m high and 3 m wide in a previous paper[11] as shown in Figure 3(A). It corresponds to an outer wall of seven storeys high and six dwelling units wide for real apartment buildings. In that study neither balustrades nor separation walls were installed. In this study, to make the model more similar to a real apartment building the scale is one-third and both balustrades and separation walls were installed on the outer wall of each floor.

It is believed that the balcony configuration influences flows into and out of the opening, flow outside the fire room, and fire characteristics in the fire room. To get knowledge on the influences of balcony configuration, an experimental study was done by using a reduced-scale model of a high-rise apartment building. Temperatures inside and outside the fire room were measured and analysed. Also computer simulation was done using a CFD software. Both results were compared.

2. Method

A reduced scale model of an apartment building was constructed with a balcony configuration seen on a real apartment building. Figures 3(B) and 4 show the configuration of the model building. The model building consisted of a fire room, outer wall, and balconies. The dimensions of fire room were 2000 mm wide, 1200 mm deep, and 750 mm high. The outer wall measured 6000 mm wide and 4000 mm high. The floor of the fire room was 800 mm above the bottom of the outer wall. The bottom of the outer wall was placed on the floor of the experimental facility used in the research. It is defined that fire room is on the first floor. Floor height was 800 mm. The dimensions of the opening were 900 mm wide and 600 mm high. The outer wall of the model building corresponded to that of a four-storey building of three rooms wide. The balconies were set on the floor of each storey. The balcony set 800 mm above the bottom of the outer wall is defined as the 1F balcony. Balcony configurations were shown in Figure 5 and Table 2. The balcony configurations shown in (a), (b), (c), and (d) were selected from typical balcony configurations seen in real apartment buildings. The balcony configuration shown in (e) is not typical but was selected for comparison and for studying the effects of balcony depth. For configurations (a), (b), (c), and (d), the balcony depth was 50 cm and the separation wall was installed at every storey. For configuration (e) neither separation walls nor balustrades were installed. The depth of balcony was varied from 0 to 50 cm at 10 cm interval.

Thermocouples (alumel-chromel type, bare-type, wire diameter : 0.64 mm or 0.32 mm) were placed in the fire room and on a plain perpendicular to the outer wall and passing through the A-A' line. Figure 6 shows the locations of the thermocouples on the plain. The average of the temperatures at the circled points in the fire room is defined as fire room temperature.

Fuel gas (LPG) was supplied through gas burners placed on the fire room floor. Heat release rate in the fire room was controlled by varying the fuel supply rate. Heat release rates were increased stepwise. The heat release rates were 0.17, 0.26, 0.30, 0.34, 0.39, and 0.43 MW. The heat release rate (Q) of each step was kept at each step for ten minutes. After that, the heat release rate was increased to the next higher step. Heat release rate was calculated assuming that the fuel gas undergoes complete combustion in fire room. The authors did not check whether complete combustion was accomplished, for example, by measuring oxygen concentration of hot gas ejected out of the opening.

Wide varieties of balcony configurations are found in real apartment buildings. Balcony configurations of real apartment buildings around our laboratory were photographed. Using the photographs typical balcony structures were selected.

Temperatures were calculated using a CFD simulation software (NIST Fire Dynamic Simulator). Fire Dynamic Simulator (FDS) is a large eddy simulation fire model which is being developed at NIST to study fire behaviour. A detailed discussion of FDS is found in references 12 and 13. Experimental results were compared with results obtained by calculation.

3. Results and Discussions

Figures 7(A) and (B) show the variation of temperature in the fire room with heat release rate. As heat release rate increases, temperature in the fire room becomes high. As shown in Figure 7(A), temperatures for configurations (a) and (c) are higher than those for other configurations. As shown in Figure 7(B), temperatures for configurations (e)d=40 cm and (e)d=50 cm are higher than those for balconies of shorter depths. Temperature in the fire room varied with balcony configuration even when opening size, opening shape, and heat release rate were kept unchanged. It is widely believed that the fire characteristics in fire room are controlled by opening size and shape. The results do not support that belief. Since the temperature in the fire room becomes high with the increase in heat release rate, it is believed that sufficient air was supplied into the fire room through the opening. It is believed that inflow of air, outflow of hot gas, and radiative heat loss through the opening were restricted by installing balustrade, separation wall, and balcony and therefore temperature in the fire room increased.

To evaluate the effects of balcony configuration an 'enclosure ratio' was introduced. As shown in Figure 8 suppose an imaginary rectangular box covering the opening. Its corners are E, F, G, H, E', F', G', H'. The enclosure ratio is a value which shows how much of surface area of the box (excluding surface passing E', E, H, and H') is covered with separation wall, balustrade, and balcony. Values are shown in Table 3. The temperature in the fire room increased with the enclosure ratio as shown in Figure 9. Effects of balcony, balustrade, and separation walls on the incoming and outgoing flows are assumed to be equal in defining the enclosure ratio. Further refinement of the enclosure ratio is needed.

Isothermal lines were drawn to get a picture of the behaviour of ejected hot gas. Figure 10 shows isothermal lines on the plain perpendicular to the outer wall and passing the A-A' line for Q=0.34 MW. The temperature profiles of ejected hot gas depicted by isothermal lines varied with balcony configuration. Comparing isothermal lines for configurations (e)d=0, (e)d=10 cm, (e)d=20 cm, (e)d=30 cm, (e)d=40 cm, and (e)d=50 cm, ejected hot gas rises farther from outer wall as balcony depth increased. Thus temperatures in the space between 2F balcony and 3F balcony and that between 3F balcony and 4F balcony become low. Comparing isothermal lines for configurations (a), (b), (c), (d), and (e)d=50 cm ejected hot gas rises near balustrade when balustrade is installed. The temperatures between 2F balcony and 3F balcony and those between 3F balcony and 4F balcony become high due to the hot gas was closer to the outer wall when balustrade was installed.

The relationship between the probability of upward fire spread and the balcony configuration is evaluated. For that purpose, the temperatures at places corresponding to the window on upper floors and the temperatures at places corresponding to the exits of balconies on upper floors were used. Window glass breaks and fire spreads into the room above the storeys of fire rooms after the window glass is heated by the hot gas flowing from the lower floors. Observing real apartment buildings, wet clothes or futons are hung near the exits of balconies in sunny days. If combustibles such as clothes and futons are heated and ignited, heat transmitted to the window glass increases. It is believed that the probability of upward fire spread becomes high when both temperatures on the outer wall and the exit of the balcony are high. The relationship between the average of the temperatures on the outer wall (Twav) and the average of the temperatures at the exit of balcony (Teav) is shown in Figure 11. Their definitions are shown in Figure 6. As shown in Figure 11, both Twav and Teav for configurations (a), (b), and (c) are high. Both Twav and Teav for configurations (e)d=30 cm, (e)d=40 cm, and (e)d=50 cm are low. The probability became high if both balustrade and separation walls were installed. The probability became low if neither balustrade nor separation walls were installed and depth of balcony was large. The evaluation of probability of upward fire spread discussed here is applicable only to fire spread by ejected hot gas. The discussion is not applicable to fire spread by other mechanisms, for example, by breaking of window glass by radiative heat from an adjacent building on fire.

Temperatures were calculated using a CFD simulation software (NIST Fire Dynamic Simulator). Using temperatures obtained by calculation, isothermal lines were drawn and shown in Figure 12. Temperatures obtained by calculations were lower than those by experiments. Comparing pictures shown in Figure 10 and those shown in Figure 12, temperature obtained by calculation was in qualitative agreement with experimental results.

4. Conclusions

Upward fire spread in fire-resistive buildings are caused mainly by ejected hot gas flowing out through openings. This type of fire spread occurs mostly in apartment buildings. Most apartment buildings have balconies. It is considered that air flow in through the opening, flow of hot gas out through the opening, and flow of hot gas rising outside the fire room are influenced by balcony configurations, if hot gas is ejected out through the opening from a fully developed fire. Knowledge on those influences are necessary for prevention of upward fire spread. To obtain that knowledge an experimental study was done using 1/3-scale model of high-rise apartment buildings. Temperatures inside and outside the fire room were measured by thermocouples and analysed. Also temperature was calculated by CFD software. Experimental results were compared with results obtained by calculation. The following conclusions were derived.

1)Temperature in the fire room varied with balcony configuration even when opening size, opening shape, and heat release rate were the same. It is because the balcony configuration affected air flow in through the opening, hot gas flow out through the opening, and radiative heat loss through the opening. To evaluate those effects of balcony configuration, an 'enclosure ratio' was introduced. Temperature in the fire room increased with the enclosure ratio.

2)Isothermal lines were drawn from temperatures measured by thermocouples. As the depth of the balcony increased, ejected hot gas flowed farther from the outer wall. If balustrades were installed, ejected hot gas flowed along balustrade.

3)The probability of upward fire spread caused by ejected flames out of the opening was evaluated by temperatures on the outer wall and temperatures at the exits of balcony. If both temperatures were large, the probability became large. The probability became large if both balustrade and separation walls were installed. The probability became small if neither balustrade nor separation walls were installed and depth of balcony was large.

4)Temperature obtained by CFD simulation was in qualitative agreement with experimental results.

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Table 1. History of the research

Year	Experiment		Image analysis, modelling, and simulation	Field study
	1/7-scale	1/3-scale		
1997-1998	Model building with two opening was used. LPG was used as fuel. Fuel supply rate and balcony depth were changed.			Use of balcony of apartment buildings was studied. Mass and location of combustibles in dwellings were investigated.
1998-1999	Model building with one opening was used. LPG was used as fuel. Fuel supply rate, opening width, and balcony depth were changed.		Flame height and location of flame tip were acquired by image analysis of videotape recording flames ejected from the opening of 1/7-scale model building.	
1999-2000		Model building with one opening was used. LPG was used as fuel. Fuel supply rate, opening width, and balcony depth were changed.	Flame height and location of flame tip were acquired by image analysis of videotape recording flames ejected from the opening of 1/3-scale model building.	Balcony structures of apartment buildings were collected by taking photographs around the authors' laboratory.
2000-2001	Model building with one opening was used. It was located under hood to measure heat release rate. LPG and solid were used as fuel. Balcony depth, opening width, fuel supply rate of LPG, and kinds of fuel were changed.	Model building with one opening was used. LPG was used as fuel. Fuel supply rate, balcony structure, and balcony depth were changed.	Semi-empirical method to predict flame height and heat flux was obtained.	
2002-2003		Model building with one opening was used. LPG and solid were used as fuel. Balcony depth, fuel supply rate of LPG, and kinds of fuel were changed.	Semi-empirical method to predict flame height and heat flux was obtained. Computer simulation of fire behaviour was done using FDS.	

Table 2. Balcony configuration

	Balustrade	Balustrade configuration	Separation wall	Depth of balcony
(a)	Yes	No break	Yes	50 cm
(b)	Yes	Rectangular break in front of opening	Yes	50 cm
(c)	Yes	Horizontal break at bottom	Yes	50 cm
(d)	No		Yes	50 cm
(e)	No		No	0, 10cm, 20cm, 30cm, 40cm, 50cm

Table 3. Enclosure ratio

Balcony configuration	Enclosure ratio
(a)	0.80
(b)	0.73
(c)	0.77
(d)	0.61
(e)d=0	0
(e)d=10 cm	0.092
(e)d=20 cm	0.18
(e)d=30 cm	0.28
(e)d=40 cm	0.37
(e)d=50 cm	0.46

d: depth of balcony

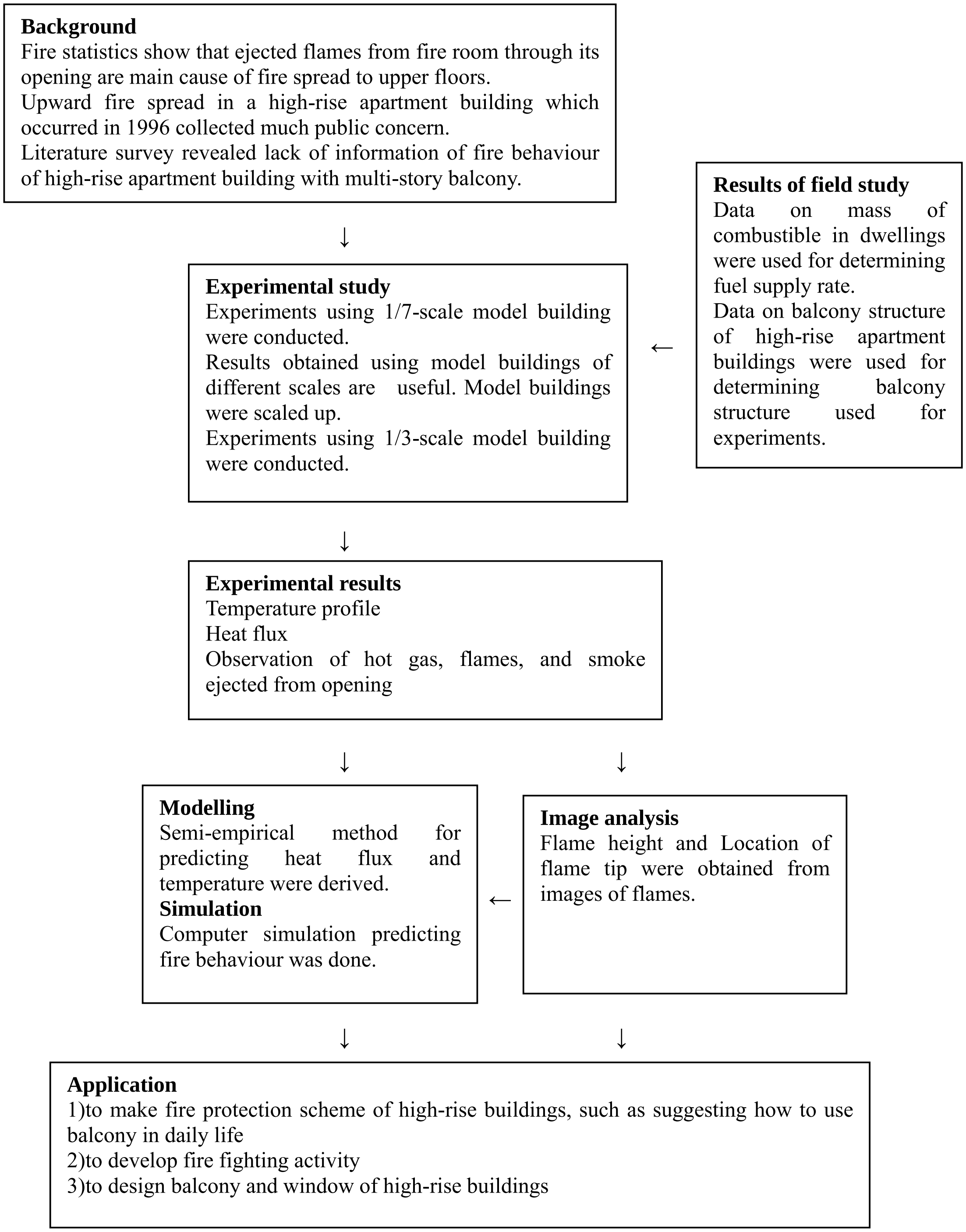


Figure 1. Flow of the research

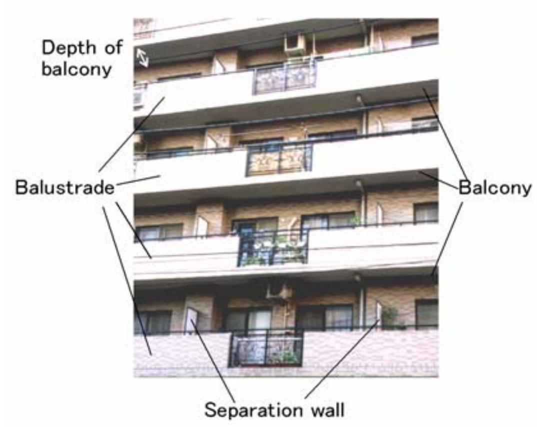
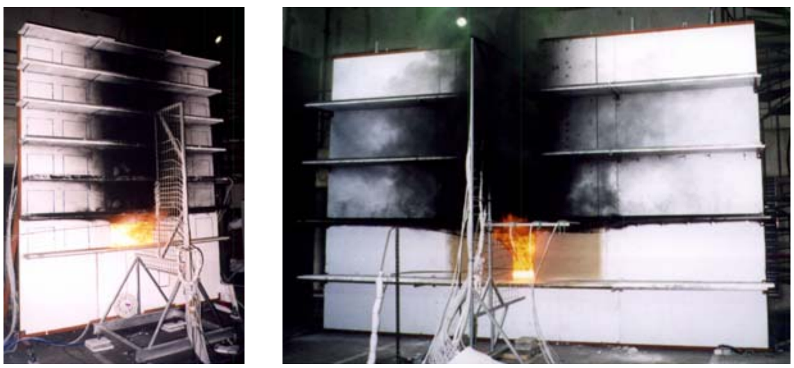


Figure 2. Typical balcony configuration of a high-rise apartment building.



(A) (B)

Figure 3. Reduced-scale model buildings used in the research.
(A) 1/7-scale model building with one opening. (B) 1/3-scale model building.

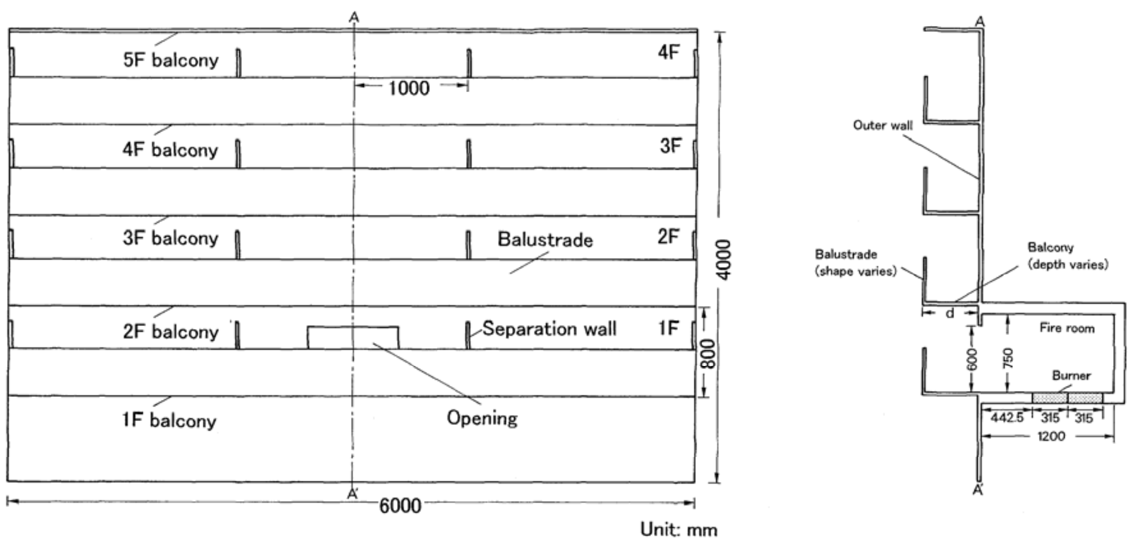


Figure 4. Configuration of 1/3-scale model building.
Left: front view, right: side view.

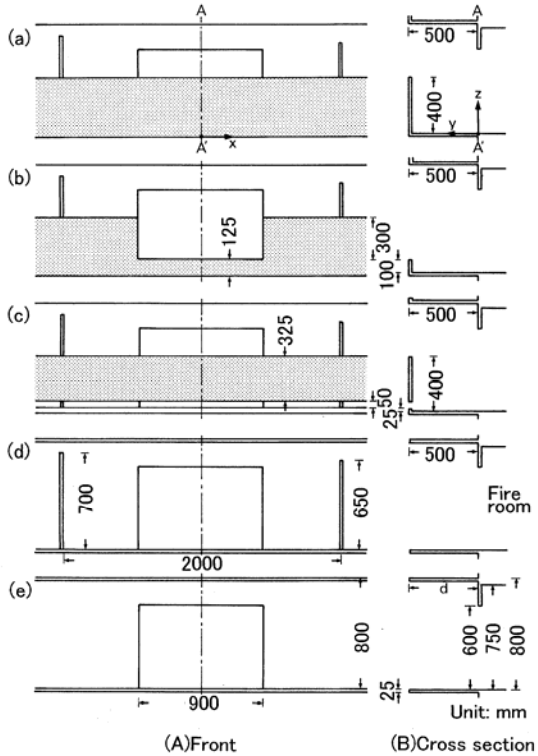


Figure 5. Balcony configuration.

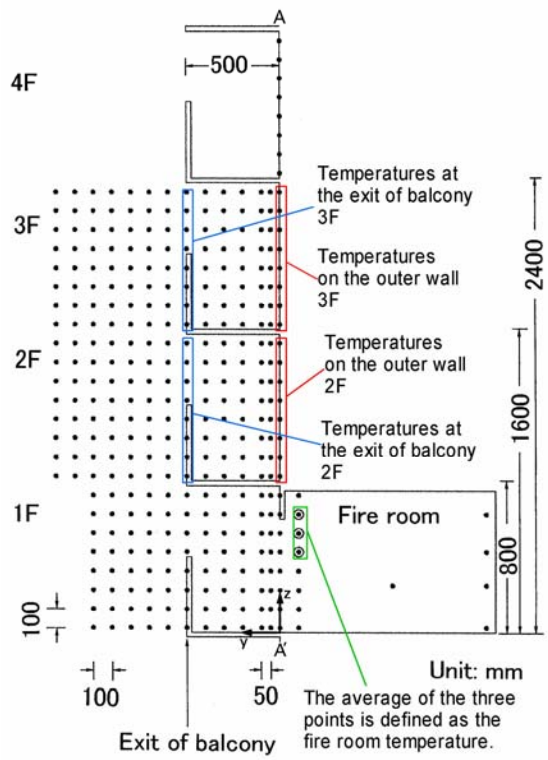
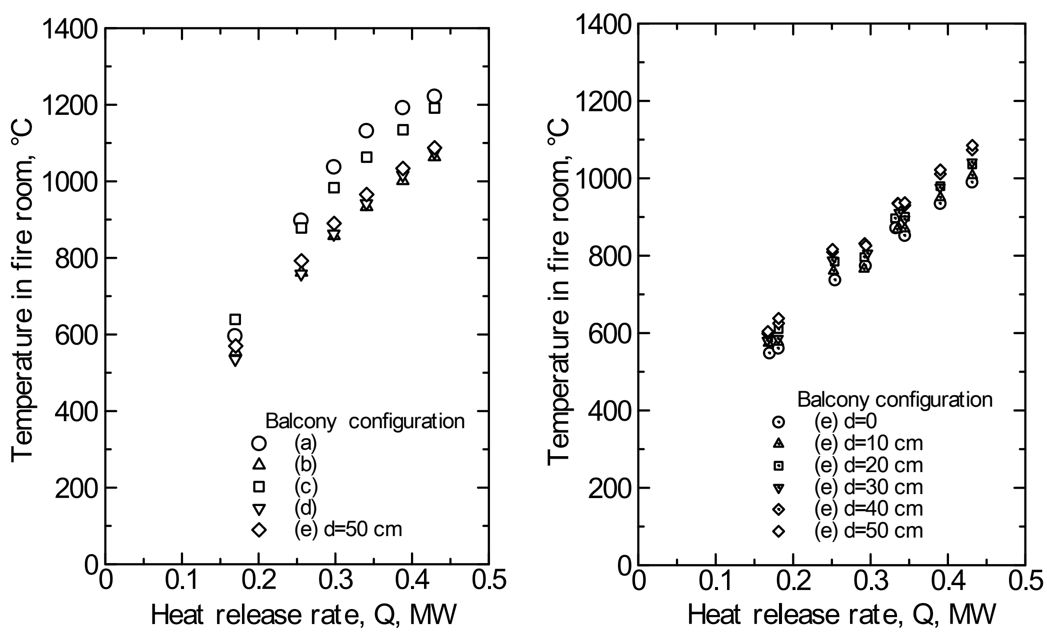


Figure 6. Locations of thermocouples on a plain perpendicular to the outer wall and passing the A-A' line.



(A) (B)

Figure 7. Variation of temperatures in the fire room with heat release rate.

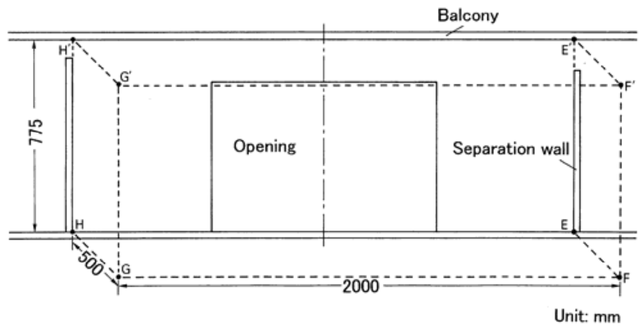


Figure 8. Outline of enclosure ratio.

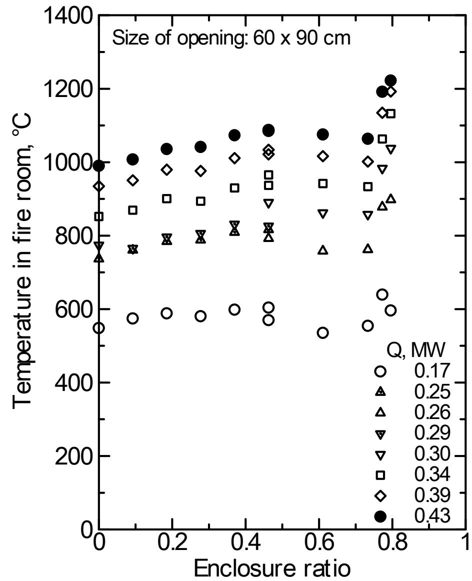


Figure 9. Variation of temperatures in the fire room with enclosure ratio.

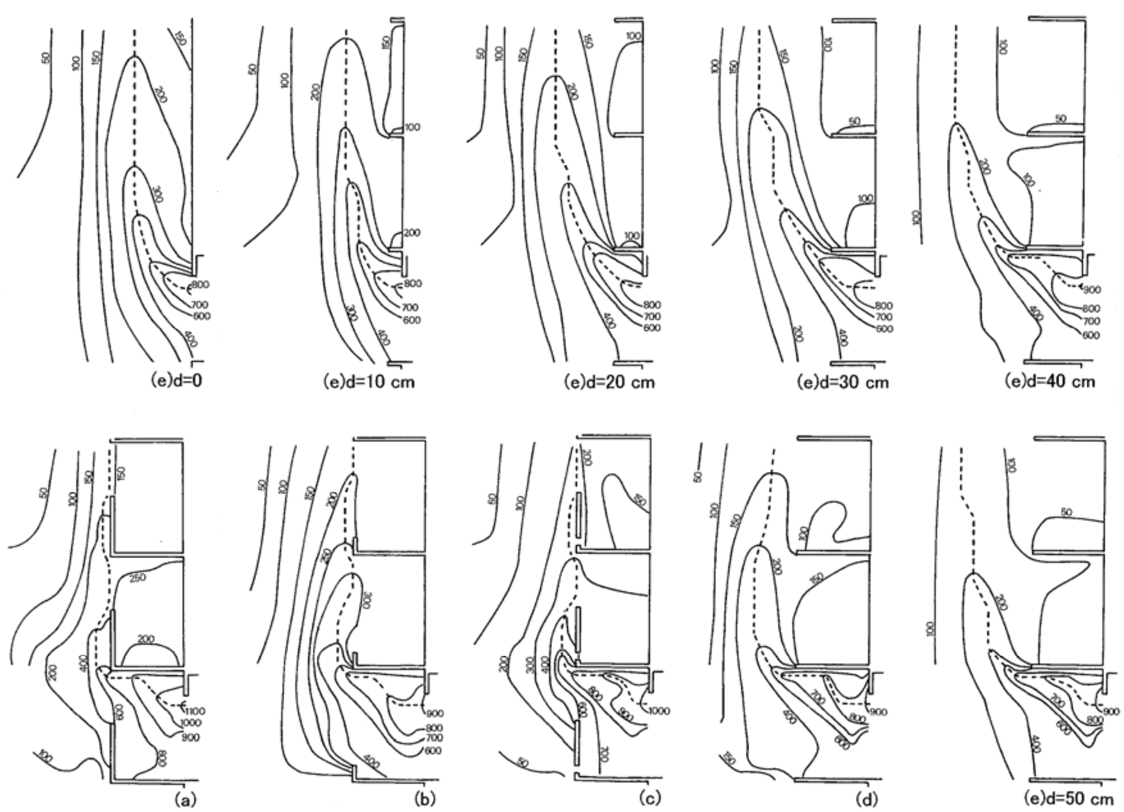


Figure 10. Isothermal lines on a plain perpendicular to the outer wall and the line passing A-A' line. Heat release rate Q=0.34 MW.
Unit: °C.

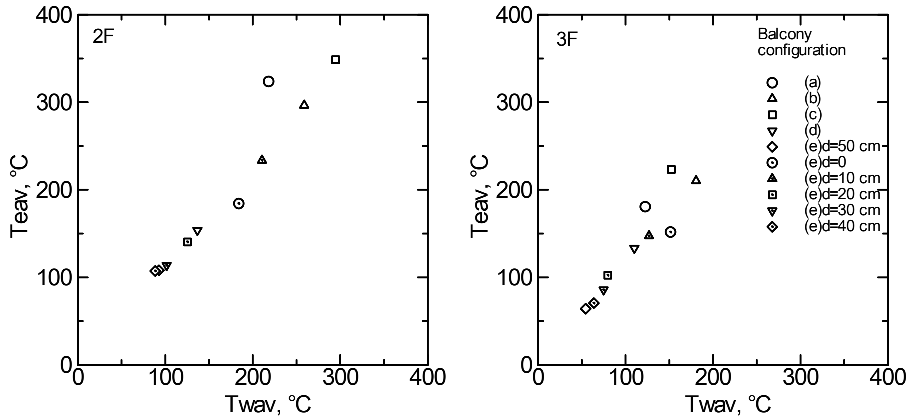


Figure 11. Relationship between the average of temperatures on the outer wall and the average of temperatures at the exits of balcony.
Left: 2F, right: 3F.
Heat release rate Q=0.34 MW.

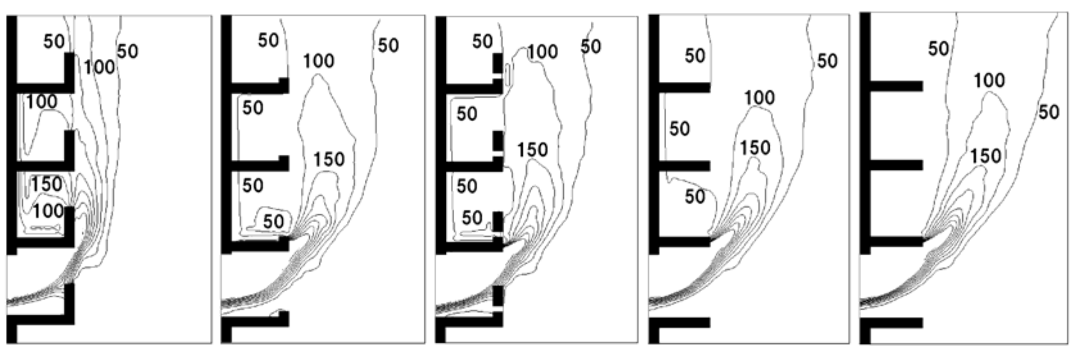


Figure 12. Isothermal lines drawn using temperatures obtained by computer simulation.
Heat release rate Q=0.30 MW.
Unit: °C.